



## **Design of Wind Turbines in Typhoon area**

A first study of Structural Safety of Wind Turbines in Typhoon prone areas

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## **ASEAN Wind 2005**

Feasibility Assessment and Capacity Building  
for Wind Energy Development  
in Cambodia, Philippines and Vietnam

### **Design of Wind Turbines in Typhoon area**

A first study of Structural Safety  
of  
Wind Turbines in Typhoon prone areas  
Deliverable 2

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# ASEAN Wind 2005 - Fact Sheet

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## Tasks

Task 1: Wind Resource Assessments	RISO + IED; PNOC-EDC; IE	(10.5 MM)
Task 2: Power System Analyses	RISO + PNOC-EDC; IE	(7.5 MM)
Task 3: Policy & Market Studies	RISO + IED; Mercapto; PNOC-EDC; IE	(9.5 MM)
Task 4: Technical Feasibility Studies	RISO + PNOC-EDC; IE	(10 MM)
Task 5: Economic Feasibility Studies	IED + RISO; PNOC-EDC; IE	(7 MM)
Task 6: CDM Project Studies	Mercapto + All	(5.5 MM)
Task 7: Financial Framework	IED + All	(5.5 MM)
Task 8: Dissemination	RISO + All	(4.5 MM)

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## 0 Executive Summary

This report deals with structural safety of wind turbines situated in the Philippines known as one of the most severely typhoon prone areas in the world. The main subject of the work reported on here is the derivation of safety factors to apply to characteristic loads computed from 50-year extreme 10-min mean wind speeds. Two cases have been considered:

- Evaluation of safety factors with the aim that structural safety at the Philippines should be the same as intended by the IEC 61400-1, which applies to areas like Europe where winter storms generate the extreme wind speeds.
- Cost-optimal assessment of structural safety. Here the aim has been to investigate the consequences of lowering reliability (i.e. in practical terms lowering the load safety factor). The assumption has been that people would not be near a turbine in case of a typhoon coming up. With this assumption the consequence can be evaluated purely in terms of monetary values allowing that a cost-optimal reliability level can be determined.

The well-established reliability method known as FORM (the first order reliability method) has been applied. The input to this method was assumptions about the probability distribution of the extreme wind speeds for a typical site in Europe and for the Philippines as derived in [5], which is a report from this project that is central to the work carried out here.

The most severe class in the IEC 61400-1 specifies the extreme 10-min. mean wind speed to be 50 m/s, whereas extreme 10-min mean wind speeds in the Philippines can be above 50 m/s, e.g. 55-65 m/s, but in many cases only slightly above 50 m/s, see [5]. Thus the characteristic value specified in IEC 61400-1 may be applicable in many cases. For the safety factor, on the other hand, the situation is different. There is some uncertainty associated with the study carried out here. With this uncertainty in mind the best estimate for the load safety factor obtainable with the information available in the present project is considered to be 1.7 for the Philippines if the same level of structural reliability as intended by the IEC 61400-1 is desired, where the load safety factor is significantly smaller, namely 1.35. Based on a very crude cost model the higher mean wind speed and safety factor of the Philippines will imply construction costs to increase about 20-30% relative to turbines designed according to IEC 61400-1. Because, compared to the central parts of the Philippines, the mean wind distribution is less fortunate in the northern shore zone of the Philippines, where the high extreme mean wind speeds exist the cost increase related to installing turbines in the shore zone is expected to rule out wind turbine projects in that zone.

An effort has been made in the project to investigate this subject. By an example it is illustrated how the cost-benefit can actually improve financial gain but it is not drastic compared to the reliability reduction that has to be accepted. It is stressed that the probabilistic model and cost-benefit model applied in this study is attached with some uncertainty, implying that the exact values presented can change in a closer study. To get more reliable results regarding this subject the development more refined models appropriate for typhoon conditions are recommended for future research.

Another subject of relevance to wind turbines in typhoon prone areas is the turbines' capability to yaw sufficiently during the passage of the typhoon which generally leads to loss of grid. The demand on the yawing control in this case has been subject of a preliminary investigation. It turns out that modern turbines can cope with the demand as long as they are powered. Because grid connection is almost inevitable lost during a typhoon power back-up is required.

# 1 Introduction

As indicated by the subtitle of this document general guidance to design of WTGs in Typhoon areas is not provided. Focus has been put on structural reliability – in terms of characteristic wind speed and safety factors – in extreme conditions. The question of yawing control performance in typhoon conditions relative to the possible passage of the eye of a typhoon is also mentioned but otherwise no other possibly relevant design issues are discussed. The work reported on here is intimately connected to the work reported in [5].

There is presently little experience with assessment of safety requirements for wind turbines situated in places where hurricanes or typhoons are likely to occur. To get a basis for choosing safety levels in hurricane areas the sub-task 4.2 which is reported here, was planned to include items:

- *Re-evaluation of safety levels of turbines designed according to existing IEC (International Electrotechnical Commission) standards but exposed to typhoons.* This subject consists in applying traditional probabilistic methods with input derived from the investigations conducted in relation to task 1.6 of this project. Especially the influence of statistical uncertainty is considered. The hypothesis is that safety levels lower than those known from the European continent and the alike will be the outcome.
- *Assessment of alternative safety level targets by a cost-benefit approach.* An assessment of economical optimal safety levels will be carried out. For a wind farm hit by a hurricane it could be argued that the presence of humans is unlikely. Thus, assessing safety level targets from a purely cost-benefit analysis involving initial construction costs, re-construction costs, the inconvenience to the society caused by the loss of power supply from a farm that collapsed due to a hurricane, the probability of a hurricane, and the expected annual benefits from the wind farm will be investigated.

Most of the results reported here have previously been reported in sections of [1]. These sections have formed the basis of the present document; however some of the models have been updated.

## 1.1 Lessons learned

Regarding the two items listed above the main outcome of the present study and the opinion about these are:

- *Re-evaluation of safety levels of turbines designed according to existing IEC (International Electrotechnical Commission) standards but exposed to typhoons.* The safety level and the demands to the yawing control have been investigated. The safety level is expressed in terms of a characteristic mean wind speed, and a safety factor. Regarding the 10-min. mean wind speed the specification of the most severe class in the IEC 61400-1 is 50 m/s, whereas extreme 10-min mean wind speeds in the Philippines can be above 50 m/s, e.g. 55-65 m/s, but in many cases only slightly above 50 m/s, see [5]. Thus the characteristic value specified in IEC 61400-1 may be applicable in many cases. For the safety factor, on the other hand, the situation is different. There is some uncertainty associated with the study carried out here. With this uncertainty in mind the best estimate for the load safety factor is 1.7 for the Philippines if the same level of structural reliability as intended by the IEC61400-1 is desired, where the load safety factor is significantly smaller, namely

1.35. Based on a very crude cost model setup as part of the work reported here, the higher mean wind speed and safety factor of the Philippines will imply construction costs to increase about 20-30% relative to turbines designed according to IEC 61400-1. Because, compared to the central parts of the Philippines, the mean wind distribution, which together with the power curve governs the benefits of installing a turbine, is less fortunate in the northern shore zone of the Philippines, where the high extreme mean wind speeds exist, the cost increase related to installing turbines in the shore zone is expected to rule out wind turbine projects in that zone. The demand on the yawing control in case of the typhoon eye should pass over the turbine location has been subject of a preliminary investigation. It turns out that modern turbines can cope with the demand as long as they are powered. Because grid connection is almost inevitable lost during a typhoon power back-up is required.

- *Assessment of alternative safety level targets by a cost-benefit approach.* An effort has been made in the project to investigate this subject. By an example it is illustrated how the cost-benefit can actually improve financial gain but it is not drastic compared to the reliability reduction that has to be accepted. It is stressed that the probabilistic model and cost-benefit model applied in this study is attached with some uncertainty, implying that the exact values presented can change in a closer study. To get more reliable results regarding this subject the development more refined models appropriate for typhoon conditions are recommended for future research. Insurance companies and banks are most likely not willing to engage in projects associated with safety levels that may almost certainly imply loss of wind turbines in case of typhoon hitting them even though the economical risk can be controlled in the development of design guidelines by rigorous risk based reliability analyses. The mental step will simply be too large. The opinion of the authors is that safety level targets assessed by a cost-benefit approach may not be relevant.

## 2 Point of Reference

In this document the international standard IEC 61400-1 [2] is used as main reference because it is expected to be gradually accepted world wide. The design philosophy of IEC 61400-1 is not significantly different from most other current wind turbine standards. A number of wind turbine classes are defined that specifies standardised wind conditions. Seen in relation to tropical conditions like those in the Philippines the IEC 61400-1 states clearly that, quote “The particular external conditions defined in classes I, II, and III are neither intended to cover offshore conditions nor wind conditions experienced in tropical storms such as hurricanes ...” unquote. Therefore one cannot be sure that design made according to the IEC 61400-1 will ensure sufficient structural reliability of turbines in regions of the world where tropical cyclones occur – that is, if one by “sufficient reliability” understands that the same reliability level as aimed at in e.g. European regions. On the other hand national building standards cannot be applied to wind turbine design either, because the design of wind turbines are driven by an equal mix of fatigue loads, loads from extreme environmental conditions (i.e. storms), and extreme loads during operation. Local standards will of course account for the severity of tropical cyclones where relevant, but they will most likely miss load cases important for wind turbine design because they are typically limited to structures that can be assumed to behave statically in response to wind loads. The fact that wind turbines are equipped with a control and safety system implies that a lot of different considerations shall be made regarding the possible malfunction of the control system, e.g. in consequence of grid loss, and

the demands on structural strength in case of such malfunctioning. IEC 61400-1 has several crucial load cases that address these issues.

As mentioned above most current wind turbine standards include load cases for operational conditions and extreme environmental conditions. It might be that extreme operational gusts and other operational conditions defined in the IEC 61400-1 will not apply to areas with tropical cyclones as well as the extreme conditions clearly do not. That this may be the case follows from the fact that at the east coast of the Philippines the strongest extreme wind conditions prevail whereas the annual mean wind speed is lower (up to 1m/s) than in the centre of the Philippines. In this respect it is important to note that IEC 61400-1 defines the ratio between extreme wind speeds and the annual mean wind speed to be exactly 5, which cannot be expected to also be the case in typhoon prone areas. Though the operational conditions are not irrelevant this document deals only with the extreme wind speeds experienced in cyclones. In this initial work this approach has been chosen because the experience up to date shows that fatal turbine failures in areas with tropical cyclones are almost exclusively related to the passage of cyclones. So this is the obvious place to start in the attempt to improve structural reliability of wind turbines in such areas.

### 3 Impacts on Design

When deciding what should be the design requirements for tropical cyclone conditions, the fundamental question to answer is: is it at all economically feasible to design turbines to survive such cyclones? In this document this question is not addressed in detail, however a simple model for construction costs is put up that would be helpful in the evaluation of feasibility. Rather the approach is taken to investigate what will be required to establish design requirements that will ensure structural reliability similar to that intended by the IEC 61400-1 standard. It is the authors' best belief that there are two main concerns regarding extreme loads in tropical cyclones

- What should be the safety factor to associate with the 50-yr wind speed, and
- What should be the demands to the control and safety system.

To take the later first; should that case occur that the eye of the cyclone passes over the turbine site the demands on yaw speed can potentially be high because of the possibly steep descent of the wind speed as one crosses through the eye-wall into the eye. After that follows a 180° change of wind direction as the eye-wall on the other side of the eye approaches. The change in wind direction can be rather drastic if the wind speed grows rapidly close the eye-wall. Initial investigations of the issue has been made that seem to indicate that the controls of modern wind turbines can keep up with the wind direction change as long as they are powered, e.g. by power back-up or battery. There are however some exceptions, see the project report [5] for further details.

The first concern listed relates to the level of structural safety provided that the control and safety system performs as required, i.e. as explained in the previous paragraph. The level of reliability is defined through the specification of the characteristic wind speed, which is the 50-yr wind speed in the case of the IEC 61400-1, in combination with the safety factor. The safety factor is needed to provide higher reliability than what is implied simply by designing to survive the 50-wind speed. Heuristically put, the purpose of the safety factor is to ensure



that the design can survive loads of a longer return period than 50 yrs, say 1500 yrs. That is, said quite simplistically, that the load factor is in a certain sense the ratio of the 1500-y r load to the 50-yr load. Having this simplistic understanding in mind it is obvious that climates with higher variability of extreme wind speeds than others must have higher safety factors if the same reliability is desired. In the following we will demonstrate that this is indeed the case for the typhoons passing the Philippines relative to the North European climate and similar climates which have been the prime concern in the formulation of IEC 61400-1. So, there are two parameters that govern design loads: 50-yr wind speed that signifies the level of extreme wind speeds, and the load factor that accounts for the inherent variability of the extreme wind speeds. The variability will in the remainder of this document interchangeably be termed uncertainty, because it represents the uncertainty the designer have regarding the likelihood that the structure will not survive extreme wind speeds.

In the following sections a preliminary investigation of the need for change of safety factors if a level of reliability level similar to that intended in the IEC 61400-1 should be desired in the Philippines. It is stressed that this work rests on the approach to extreme value statistics in typhoons described in another project report [5] – namely a methodology based on satellite images. For instance it is noted that the uncertainty in determination of pressure etc. from satellite images is considerable, and may well exceed what can be covered by safety factors. An attempt to verify the work reported in [5] against ground measurements has been made. However some uncertainty about its reliability remains. Therefore the following steps are taken: 1) first a simple reliability assessment for a typical North European environment is considered as the point of reference, and next 2) different assumptions about the Philippine typhoon environment are considered leading to the calibration of different load safety factors whereby a range of likely values of the load safety factor is obtained. By establishing such a range the implication of uncertainty in the methods to derive the extreme wind conditions is made apparent, and it provides, so to say, a table to look up a safety factor, in case one should decide on a specific extreme wind distribution.

## 4 Reliability Model

The reliability assessment consists in an evaluation of the probability of structural failure. To this end one needs an equation for the failure limit state, a probability model describing the probability distributions of all relevant variables influencing the reliability, i.e. wind speeds, material strengths, and model uncertainties. Further one needs to define characteristic values for materials and for loads (i.e. the 50-yr mean wind speed), and one needs the relevant load and strength safety factors. The model assumption made here has been adopted from [3] (of which a short presentation is given in [4]). The reader is referred to these references on the details of the model. The failure limit state defines the boundary between situations where the wind turbine structure will survive the loads, and situations where it will not. Obviously a definition of the limit between failure and safe is needed to compute the probability of failure. Applying, for simplicity and transparency, the Davenport model, see e.g. [10], the failure limit state is expressed as

$$f_y = c_{\text{inf}} U_{\text{hub}}^2 \underbrace{(1 + 2k_p I c_{\text{amp}})}_{c_{\text{dyn}}} \quad (1)$$

Basically the formula says that the load is proportional to the mean wind squared augmented by a peak factor. Thus the factor  $c_{\text{inf}}$  is an influence number relating the load to the product  $U_{\text{hub}}^2 c_{\text{dyn}}$  of the mean wind pressure and the dynamic response factor. The influence number depends on the design of the turbine; among others  $c_{\text{inf}}$  depends on the geometry of tower and the blades, and the lift and drag coefficients. It also accounts for the air density  $\rho$ . The factor  $c_{\text{dyn}}$  is the dynamic response factor given by the peak factor  $k_p$ , the along wind turbulence intensity  $I_1$ , and the factor  $c_{\text{amp}}$  which accounts for dynamic amplification and for admittance. Because the admittance depends on lift and drag coefficients,  $c_{\text{amp}}$  depends on the design of the turbine just like  $c_{\text{inf,aero}}$  does. Finally the peak factor depends on the response frequency  $f_0$  implying that  $k_p$  depends on the design too. The expression in Eq. (1) is believed to represent well the tower bottom response but it is not necessarily well-suited for blades. Finally  $f_y$  denotes a generic material strength.

The reliability  $R$  is the probability that the structure survives the loading, i.e. the complement of the probability of failure:

$$R = 1 - \Pr\{\text{failure}\} \quad (2)$$

Traditionally the probability of failure is the corner stone in evaluation of structural reliability. Thus we will focus on this probability here too. Typically it is quantified with reference to a one year period, i.e. the failure probability,  $p_f$ , is computed as the probability per year which has unit  $\text{yr}^{-1}$ . If, as a starting point, we neglect model uncertainties, the probability of failure becomes

$$p_f = \Pr\{F_y \leq F\} = \Pr\{F_y \leq c_{\text{inf}} U_{\text{hub}}^2 (1 + 2D_{\text{dyn}} I c_{\text{amp}})\} \quad (3)$$

Relative to Eq. (1) the quantities  $U_{\text{hub}}$  and  $I$  must now be interpreted as random variables. Since the realisation of the spectrum changes all the time the dynamical amplification  $k_p$  must be replaced by a random variable, here denoted  $D_{\text{dyn}}$ . Further  $F_y$  has been introduced as a generic random material strength. This is done because in reality the strength does not have exactly the same value for all fabricated steel. Likewise the maximum wind speed and turbulence in the lifetime of a turbine is not a predefined value – it is inherently random. This is why the reliability is expressed in terms of a probability. Instead of the maximum wind speed in the lifetime it is custom to use the annual maximum wind speed. By this one obtains that  $p_f$  becomes the annual probability of failure, i.e. the probability of failure with reference to one year. To mark the change to random variables the quantities have been written in capitals (if they not already were).

Now there are also uncertainties related to the modelling of the turbine. For instance modelling the structure rests on a number of assumptions rendering the eigenfrequencies different from what will be experienced in reality. More important are the uncertainties related to the modelling of the wind loads following from the aerodynamic modelling and the modelling of ground roughness. Such uncertainties are known as modelling uncertainties and are also represented by random variables. Finally there are also statistical uncertainties. These are related to the estimation of e.g. the annual extreme wind distribution. Often a Gumbel distribution is

fitted to measured extreme winds. Estimating parameters is associated with uncertainty, and whether to choose a Gumbel or another distribution type may be categorized as modelling uncertainty. Quantifying modelling uncertainty is difficult, or even impossible, as modelling uncertainties are supposed to bridge the gap between models and reality. Some of this gap we know about because of deliberate simplifications used in our models, whereas the rest of the gap represents simplifications unknown to us. Enhancing now Eq. (3) to account for modelling uncertainties too we may write

$$p_f = \Pr\{F_y X_m \leq c_{\inf} U_{\text{hub}}^2 X_U X_{\text{aero}} (1 + 2D_{\text{dyn}} X_{\text{dyn}} I c_{\text{amp}})\} \quad (4)$$

Additionally four uncertainty variables,  $X_m$ ,  $X_U$ ,  $X_{\text{aero}}$ , and  $X_{\text{dyn}}$  have been introduced to account for uncertainty in modelling of material strength, modelling and statistical estimation of the extreme wind distribution, uncertainty in modelling of aerodynamic loads, and uncertainty in modelling of dynamic response, respectively. The turbine specific quantities, such as  $c_{\inf}$ ,  $c_{\text{amp}}$ , and  $k_p$  need be fixed before an evaluation of  $p_f$  can take place. These quantities are determined via an inequality known as the design inequality. This inequality states the requirements specified by the design rules, namely that the design strength must be greater than or equal the design load – obtained, respectively, by dividing and multiplying the characteristic values by the respective partial safety factors. That is:

$$\frac{f_{y,c}}{\gamma_m} \leq \gamma_f c_{\inf} U_{\text{hub},c}^2 (1 + 2k_p I_c c_{\text{amp}}) \quad (5)$$

Relative to the limit state equation in (1) safety factors have been added, and strength, wind speed and turbulence intensity have been replaced with characteristic values (index  $c$  added), and the equality sign has been substituted by an inequality sign. A design is said to be “designed to the limit” if the strength and load side are equal. If it is not designed to the limit, it is not cost optimal and conservative. For the present study (as it is custom) we consider only structures designed to the limit because this will give the minimum value for the structural reliability, i.e. the maximum probability of failure. It is noted that for a structure there are in reality many design inequalities to fulfil, e.g. for fatigue, extreme and serviceability load cases, implying that in practice a structure is not designed to the limit with respect to all loads, but it may still be cost optimal. However for a study of reliability it is still quite indicative to assume design to the limit for each separate load case. Thus we consider here the design equation derived from Eq. (5). Note that the safety factors have been collected on the left-hand side:

$$\frac{f_{y,c}}{\gamma_f \gamma_m} = c_{\inf} U_{\text{hub},c}^2 (1 + 2k_p I_c c_{\text{amp}}) \quad (6)$$

Now, dividing each side of this design equation into the respective sides of the inequality in formula (4) yields that the probability of failure can be expressed by

$$p_f = \Pr\left\{\gamma_m \gamma_f \frac{F_y}{f_{y,c}} X_m \leq \frac{U_{hub}^2}{U_{hub,c}^2} X_U X_{aero} \frac{1 + 2D_{dyn} I_c c_{amp} X_{dyn}}{1 + 2k_p I_c c_{amp}}\right\} \quad (7)$$

The denominator on the right-hand side of the inequality gives the characteristic value of the 10-min maximum response. This characteristic value is the expected value of the 10-min extreme response. Typically the dynamic part of the response contributes with half of the expected value. Thus we assume here that the denominator can be set to 2. If one defines the normalised variables

$$\tilde{F}_y = \frac{F_y}{f_{y,c}} \quad \tilde{U} = \frac{U_{hub}}{U_{hub,c}} \quad \tilde{I} = \frac{I}{I_c} \quad \tilde{D}_{dyn} = 2D_{dyn} I_c c_{amp} \quad (8)$$

which have a characteristic value equal 1.0, one ends up with

$$p_f = \Pr\left\{\gamma_m \gamma_f \tilde{F}_y X_m \leq \tilde{U}^2 X_U X_{aero} \frac{1 + \tilde{D}_{dyn} X_{dyn} \tilde{I}}{2}\right\} \quad (9)$$

The normalisation shows that for linear models like the one used here the safety factor can be determined independent of the actual value of the characteristic value. What matters is whether the characteristic value is the mean value, or, for loads, a high fractile, and, for material strengths, a low fractile.

Next step is to choose a set of distributional assumptions, known as the uncertainty model, in

Name	Description	Type	Bias	CoV	Char. value
$\tilde{U}^2$	<b>Europe:</b> Annual max 10-min mean wind <i>squared</i> and normalized by characteristic value	Gumbel	1	25%	98% 50-yr
$\tilde{U}$	<b>Europe:</b> Annual max 10-min mean wind normalized by characteristic value	Gumbel	1	12%	98% 50-yr
$\tilde{U}$	<b>The Philippines:</b> Annual max 10-min mean wind normalized by characteristic value	Gumbel	1	25-35%	98% 50-yr
$X_U$	Statistical and exposure uncertainty of $\tilde{U}$	Lognormal	1	11%	Mean
$X_{aero}$	Model uncertainty, aerodynamic loads	Lognormal	1	10%	Mean
$\tilde{D}_{dyn}$	Normalized extreme turbulent response	Gumbel	1	10%	Mean
$X_{dyn}$	Model uncertainty for dynamic response	Lognormal	1	3%	Mean
$\tilde{I}$	Normalized turbulence intensity	Lognormal	1	5%	Mean
$\tilde{F}_y$	Normalized yield strength	Lognormal	1	5%	5%
$X_m$	Model uncertainty, strength	Lognormal	1	7%	Mean

Table 1 Distribution assumptions for the uncertainty model, which covers inherent, statistical and modelling uncertainties.

order to evaluate  $p_f$ . The distributional assumptions are listed in Table 1. The first column specifies the type of distribution. The second column gives the bias which is defined as the ratio of the actual characteristic (or nominal) value to the assumed characteristic value. For strength uncertainties a bias greater than 1 implies conservatism whereas for the load side conservatism is typically implied by uncertainties with bias less than 1. For calibration studies it is good practise to assume the bias equal 1. If one assumes conservative biases one can argue that an engineer may come around that design closer to the limit than his colleagues. Then the reliabilities used in the calibration study will be optimistic, which is not desirable. The third column gives the coefficient of variation (CoV), which is defined as the ratio of the standard deviation to the mean value, i.e.  $\text{CoV} = \sigma/\mu$ . This is a convenient number for the following reason. Heuristically put, the safety factor covers the gap between the characteristic value (typically the 50 year value) and the design value (of much longer return period, say 1300 years). This gap becomes larger the larger the standard deviation of the extreme wind distribution becomes. Because the safety factor is the *ratio* between the design value and the characteristic value, and because this ratio is often well reflected by the ratio of the standard deviation to the mean value, the safety factor more or less scales with the CoV. In the present case this is true and the safety factor turns out to be independent of the characteristic value as long as the CoV is the same. This is why the CoV is a very convenient number. Together with the characteristic value specified in the last column the CoV fully defines the two-parameter distributions applied in this uncertainty model. Percentages in the 'Char. value' column denote percentile. For the mean wind speed the equivalent return period is given.

For the Philippines environment the distribution of the extreme winds have been obtained from the investigations of best tracks as reported in [5]. It is emphasised that verification against ground measurements of the extreme wind statistics applied here is crucial for the validity of the results presented. Thus, the inherent uncertainty in the interpretation of satellite images applied to determine the typhoon characteristics used here can be considerable compared to the load safety factor, see [5] for details on the uncertainty of contemporary interpretation methods. In [5] it has been made probable, that the data used to obtain the stochastic model used here for the extreme mean winds are in the right range.

For the European environment a Gumbel distribution model for the mean wind speed *squared* was available (first row in Table 1), i.e. a model that assumes the mean wind pressure to be Gumbel. This is a standard model known from Danish safety factor calibration studies. For the typhoon climate, on the other hand, a Gumbel distribution model directly for the mean wind speed was available (third row in Table 1). Experience show that this difference in distribution models cannot be proven to be statistical significant. That is, a Gumbel distribution fits  $U$  and  $U^2$  equally well. Because reliability analyses are sensitive to the upper tails of the distributions of the load variables the difference in distribution models for  $U$  is prohibitive for a faithful comparison of reliability levels computed for the European conditions and the typhoon conditions. To get around this, the parameters of a Gumbel distribution for the extreme mean wind in Europe are estimated so that when the Gumbel distributed wind speed variable is squared it gets the same mean and std. dev. as the Gumbel distribution for the squared wind speed. The resulting parameters are given in the second row of Table 1. The details of this transformation are given in the Appendix.

The plot to the right in Figure 1 shows a contour plot of the variation over the Philippines of the CoV. A large difference between the coefficients of variation of the mean wind speed for

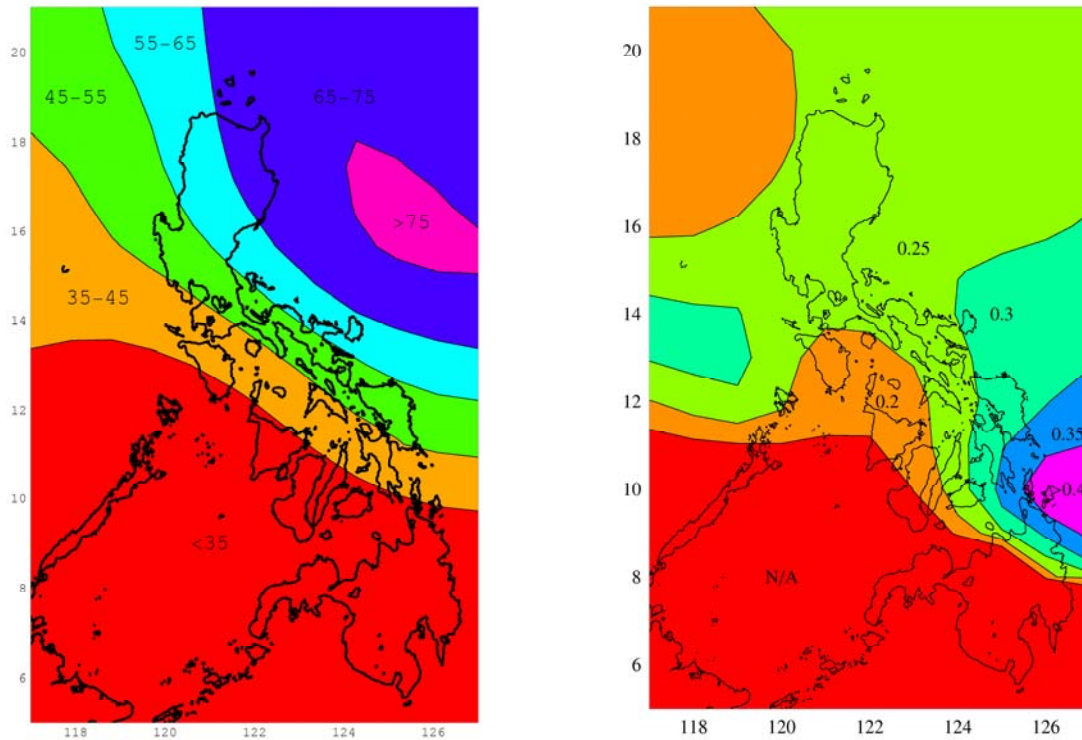


Figure 1 To the left: contour plot of the 50-year 10-min mean wind speed. To the right: contour plot of the variation over the Philippines of the coefficient of variation ( $CoV = \text{std.dev.}/\text{mean}$ ) of the annual maximum 10-min mean wind speed due to typhoons

the European environment and for the Philippines environment is noted. This reflects the expected higher variability of the extreme winds generated by typhoons. The CoV ranges from 20% to 35%. In Table 1 the range 25% to 35% is specified as values of interest for a parameter study. Like the 50-yr wind speed changes significantly across the Philippines, so does the CoV, see the left hand plot in Figure 1 (this plot is taken from Figure 14 in [5]). The pattern is identical, however the trend is the same, i.e. increasing value as one moves from east to west. Since 35% is only realised in a smaller portion of the Philippines,  $CoV=30\%$  will be used here as the representative value, though conservative for many cases. In lack of information about the turbulence intensity in typhoons it is assumed that the same distribution model applies.

As mentioned modelling uncertainties are hard to establish. Nonetheless some experience has been built up. This is reflected by the numbers given in the table. The uncertainty about the modelling uncertainties can be lived with because in a calibration study we are going to make a comparison of the reliabilities. The comparison means that the absolute value of the reliability is less important than the relative values. Thus an error in modelling uncertainties affects the computed reliability in the same direction for both the European and the Philippine environment. Further the uncertainty of the extreme wind speed is much higher than the modelling uncertainties. Clearly it is much more important to have proper models of the mean wind speed distributions.

## 5 Cost-benefit model

To provide a tool that can give an idea about the increase in construction costs in relation to an increase in design wind loads an approximate model is proposed here. If benefits and failure costs are added, such a cost model can also be used in a cost-benefit optimisation of the reliability level which was the second issue to deal with in this project sub-task.

The model proposed below gives the relative change in construction costs for a relative change in extreme storm/typhoon loads. It is based on present experience with turbines designed according to IEC 61400-1. Such designs reflect a certain balance between the importances of extreme loads relative to fatigue loads in terms of being design driving for the various main components of a turbine. This balance might be different for typhoon areas like the Philippines, because here it seems that the normal environmental conditions are milder relative to the extreme conditions than is assumed in the IEC 61400-1 [6]. Thus possibly for the Philippines a cost model should have more emphasis on extreme loads than what is proposed here, consequently rendering the model presented here non-conservative. Further it turns out that a significant increase in the load safety factor is found. This means the relative change in extreme loads become large. Therefore the proposed model is possibly extrapolated far beyond its limits of validity, implying that the results should be looked at with caution. The project does not allow for a more detailed study of these matters.

For the present cost model the grid connection costs are disregarded. The foundation contribute about one sixth of the total costs and the turbine is responsible for the remainder. For the turbine; the rotor, the nacelle, and the tower each contribute about one third of the costs. The rotor-nacelle-assembly design is assumed driven by fatigue, which may be debatable for designs in typhoon prone areas. About one half of the tower costs are assumed driven by extreme loads, and similarly one half of the foundation costs are also assumed driven by extreme loads. The extreme load driven costs are assumed proportional to the load which in turn is proportional to the square of the mean wind speed and directly proportional to the load factor. With these simplifying assumptions the relative cost change due to changes in extreme mean wind speed becomes

$$\frac{C_I}{C_{\text{ref}}} = \underbrace{\frac{1}{6} \left( \frac{1}{2} + \frac{1}{2} \frac{\gamma_f}{\gamma_{f,\text{ref}}} \frac{U_c^2}{U_{c,\text{ref}}^2} \right)}_{\text{foundation}} + \underbrace{\frac{5}{6} \left\{ \frac{1}{3} + \frac{1}{3} \left( \frac{1}{2} + \frac{1}{2} \frac{\gamma_f}{\gamma_{f,\text{ref}}} \frac{U_c^2}{U_{c,\text{ref}}^2} \right) + \frac{1}{3} \right\}}_{\text{tower}} = \frac{7}{9} + \frac{2}{9} \frac{\gamma_f}{\gamma_{f,\text{ref}}} \frac{U_c^2}{U_{c,\text{ref}}^2} \quad (10)$$

In this expression the product  $\gamma_{f,\text{ref}} U_{c,\text{ref}}^2$  denotes the product of the load safety factor and mean wind speed used as reference in the present study, i.e. the safety factor and the characteristic value of the extreme wind speed used in designs made according to IEC 61400-1. We chose the most severe wind turbine class as case study, implying class IA turbines, i.e.

$U_{c,\text{ref}} = 50$  m/s. Irrespective of classes the load safety factor specified in IEC 61400-1 for extreme loads is 1.35. The alternative characteristic mean wind speed and load factor are denoted  $U_c$  and  $\gamma_f$ , respectively. Finally the ratio  $C_I / C_{\text{ref}}$  denotes the initial construction costs relative to the costs of the reference case. It is noted that extreme loads contribute only a minor part to the overall costs. In Table 2 you find evaluation of relative increase of initial costs according to the model in Eq. (10).

		Load safety factor: $\gamma_f$			
		1.7	1.8	1.9	2.0
Characteristic value: $V$ [m/s]	60	1.18	1.20	1.23	1.25
	70	1.33	1.36	1.39	1.42
	80	1.49	1.54	1.58	1.62

Table 2 Examples of discounted relative costs as function characteristic wind speed and load safety factor

Eq. (10) specifies only the cost model. For a cost-benefit study also benefits and construction costs are needed as the aim is to maximise the benefit as function of the reliability. Clearly, as the reliability goes down the construction cost decrease, while on the other hand expected reconstruction/replacement costs increase because of the increased likelihood of structural collapse. A discussion of different cost-benefit models is presented in [7]. A model is applied that assumes systematic reconstruction of turbines in case of collapse, that is, a turbine of the same type as the one collapsed is for certain used as replacement of the collapsed turbine each time a collapse occurs. With this assumption the objective function, i.e. the expected benefit minus the expected costs, normalised by the reference cost, becomes

$$G(\mathbf{z}) = \underbrace{\frac{b}{rC_{\text{ref}}}}_{\text{benefit}} - \underbrace{\frac{C_I}{C_{\text{ref}}}}_{\text{initial construction costs}} - \underbrace{\frac{C_I + C_F}{C_{\text{ref}}} \frac{\lambda_{\text{typhoon}} p_{f|\text{typhoon}}}{r + \lambda_{\text{typhoon}} p_{f|\text{typhoon}}}}_{\text{expected reconstruction and failure costs}} \quad (11)$$

where  $r$  is the rate of interest,  $b$  is the benefit (corrected for O&M expenses),  $C_F$  is the cost of failure, and  $\lambda_{\text{typhoon}} p_{f|\text{typhoon}}$  is the annual probability of failure due to typhoon, which was above denoted  $p_f$  (the  $\lambda$  is the rate of hurricanes pr. yr. and  $p_{f|\text{typhoon}}$  is the probability of failure in case of a typhoon). Thus the first term on the right-hand side gives the discounted annual profits, the second term the initial construction costs, and the last term is the discounted expected costs of collapse. On the left hand side the  $\mathbf{z}$  denotes that benefits, costs, and reliability depend on the design parameters, which are collected in the  $\mathbf{z}$ -vector. An estimate of the benefit requires a model for the power curve, a model for the mean wind distribution and an estimate of the O&M costs. The project has not allowed the time to put up all this. However in an earlier project the benefits for a European offshore site (implying high O&M expenses, 0.06 €/kWh) with a generic 2MW pitch regulated turbine was estimated to be

$$\frac{b}{C_{\text{ref}}} = \frac{1}{8} \quad (12)$$

It is noted that the exact value of the benefits does not change cost-optimal reliability in the present case, where the rotor diameter, blade profiles, and control system is not changed, only the tower and foundation geometry is assumed to change. An error in the benefits only affects the absolute value of the total benefits  $G(\mathbf{z})$ . The failure costs are probably quite small. Here we assume, rather arbitrarily:



$$\frac{C_F}{C_{\text{ref}}} = \frac{1}{36} \quad (13)$$

So, in conclusion the cost-benefit model becomes

$$G(\mathbf{z}) = \frac{1}{8r} - \left( \frac{7}{9} + \frac{2}{9} \frac{\gamma_f}{\gamma_{f,\text{ref}}} \frac{U_c^2}{U_{c,\text{ref}}^2} \right) - \left( \frac{7}{9} + \frac{2}{9} \frac{\gamma_f}{\gamma_{f,\text{ref}}} \frac{U_c^2}{U_{c,\text{ref}}^2} + \frac{1}{36} \right) \frac{p_f}{r + p_f} \quad (14)$$

## 6 Calibration results

The calibration aims at determining the load safety factor to apply in typhoon areas so that the same structural reliability is obtained as intended by the IEC 61400-1 for European environmental conditions. In mathematical terms  $\gamma_{f,\text{Philippines}}$  must satisfy the requirement in the following equation:

$$p_{f,\text{winter storm}}(\gamma_{f,\text{IEC61400-1}}) = p_{f,\text{typhoon}}(\gamma_{f,\text{Philippines}}) \quad (15)$$

This equation is solved numerically by application of the well-established reliability method known as FORM (the first order reliability method), see e.g. [11]. Table 3 lists results of the calibration for different assumptions about the distribution of the wind speeds. The two first rows give the reference case, i.e. the European condition, but with two different distributional models; the first for the wind speed squared and second directly for the wind speed. Note how different the results for the failure probability are – about a factor of 2 just by applying the same distribution type to either the extreme wind speed or the square of it. This observation gives the rationale for making the effort to transform the distribution for the European conditions from the squared mean wind speed directly to the mean wind speed. It also illustrates

Condition	$\gamma_f$	$U_c$ [m/s]	CoV( $U$ )	$p_f$	$\gamma_f U_c^2 / \gamma_{f,\text{ref}} U_{c,\text{ref}}^2$	$C_I / C_{\text{ref}}$
European	1.35	50	CoV( $U^2$ )=25%	$0.73 \cdot 10^{-3}$	1	1
do.	do.	do.	12%	$1.14 \cdot 10^{-3}$	1	1
Typhoon	1.60	60	25%	$1.16 \cdot 10^{-3}$	1.71	1.16
do.	do.	70	do.	do.	2.32	1.29
<b>do.</b>	<b>1.68</b>	<b>60</b>	<b>30%</b>	<b><math>1.17 \cdot 10^{-3}</math></b>	<b>1.79</b>	<b>1.18</b>
<b>do.</b>	<b>do.</b>	<b>70</b>	<b>do.</b>	<b>do.</b>	<b>2.44</b>	<b>1.32</b>
do.	1.75	60	35%	$1.18 \cdot 10^{-3}$	1.87	1.19
do.	do.	70	do.	do.	2.54	1.34
do.	1.82	60	40%	$1.16 \cdot 10^{-3}$	1.94	1.21
do.	do.	70	do.	do.	2.64	1.36

Table 3 Calibrated safety factors for various cases. The Typhoon case with CoV=30% is chosen to be the representative but conservative case (marked in bold typeface). The other typhoon cases are included to show the sensitivity of the result.

how difficult it is to compare failure probabilities without first deciding on a common probabilistic model. And even when that has been decided one must be careful not to interpret the obtained numbers as absolutely true results. Basically the problem is that it is hard to verify the tails of the distributions. For the strengths you have a fair chance because a lot of tests can in principle be carried out. However, for the load side one has to wait for a sufficiently long data record to build up, and because the load side in the extreme wind case is the dominant contributor to failure probability the modelling uncertainty related to the choice of tail of course has a big impact on the uncertainty of the computed failure probability. Consequently the failure probabilities must be considered as notional.

For the strength safety factor it has been chosen to set  $\gamma_m = 1.1$ . It is noted that this is a low number compared to what will be used in practice, but is a reference value corresponding to only considering inherent material uncertainty. For this reason failure probabilities computed here can be higher than what the application of other strength safety factors will yield. The authors are aware that previously published results [1] have shown lower failure probabilities. This is due to the biases greater than 1 for both  $\tilde{F}_y$  and  $X_m$  used in [1]. The biases correspond to extra strength safety factors. The biases have been cancelled here for the reasons given in relation to Table 1.

The typhoon case with CoV = 30% is chosen to be the representative but conservative case (marked by bold type face in Table 3). The other typhoon cases listed in Table 3 are included to show the sensitivity of the result. Bearing in mind that there is some uncertainty about the proper assumptions for the distribution of the extreme wind speeds in typhoons the best estimate of the safety factor is considered to be 1.7. If safety factors for other CoVs are wanted the results in Table 3 show that the following linear relation may be used

$$\gamma_f = 1.7 + 0.07 \frac{\text{CoV} - 30\%}{5\%} = 1.28 + 1.4 \cdot \text{CoV} \quad (16)$$

Table 3 also lists the ratio  $\gamma_f U_c^2 / \gamma_{f,\text{ref}} U_{c,\text{ref}}^2$  and the derived relative initial costs  $C_i / C_{\text{ref}}$ . A relative cost increase in the range from 20% to 30% is seen. Though O&M costs are important in the lifetime costs, an increase of 20% to 30% can be an economical challenge.

## 7 Cost-benefit optimized reliability level

This section presents an example of what can be achieved if the approach of cost-optimal structural safety is taken. Clearly, as the reliability goes down the construction cost decrease, while on the other hand expected reconstruction/replacement costs increase because of the increased likelihood of structural collapse. It must be expected that an optimum exist that balance failure costs and benefits. As mentioned in Section 5 various cost-benefit models can be formulated [7]. A model is applied that assumes systematic reconstruction of turbines in case of collapse, that is, a turbine of the same type as the one collapsed is for certain used as replacement of the collapsed turbine each time a collapse occurs. The objective function is given in (14). As already discussed in the previous sections the uncertainty and cost-benefit models available are not detailed and accurate enough to enough to give final answers. Therefore the results presented here can only be considered as an indicative example that illustrates the principle of cost-optimal reliability design criteria.

Condition	$r[\%]$	$b/C_{\text{ref}}$	$U_c$ [m/s]	$\gamma_f$	$p_f$	$\gamma_f U_c^2 / \gamma_{f,\text{ref}} U_{c,\text{ref}}^2$	$C_I / C_{\text{ref}}$	$G(z)$
European	5	1/8	<b>50</b>	<b>1.35</b>	<b><math>1.14 \cdot 10^{-3}</math></b>	<b>1</b>	<b>1</b>	<b>1.4770</b>
do.	do.	do.	50	1.30	$1.53 \cdot 10^{-3}$	0.96	0.99	1.4779
Typhoon	do.	do.	<b>60</b>	<b>1.70</b>	<b><math>1.10 \cdot 10^{-3}</math></b>	<b>1.81</b>	<b>1.18</b>	<b>1.29</b>
do.	do.	do.	<b>70</b>	<b>do.</b>	<b>do.</b>	<b>2.47</b>	<b>1.33</b>	<b>1.14</b>
do.	do.	do.	60	1.30	$3.90 \cdot 10^{-3}$	1.39	1.09	1.33
do.	do.	do.	70	1.20	$5.53 \cdot 10^{-3}$	1.74	1.16	1.22
do.	do.	- 3%	60	1.30	$3.90 \cdot 10^{-3}$	1.39	1.09	1.26
do.	do.	+3%	60	1.20	$5.53 \cdot 10^{-3}$	1.28	1.06	1.40

Table 4 Cost-optimal reliability – except for the first, third and fourth rows (marked by bold face) that are taken from Table 3 to serve as reference. Only the Typhoon case with CoV=30% has been considered.

Table 4 shows the results of a number of example studies. Only the Typhoon case with CoV=30% has been considered. The first two lines consider European conditions. The first line is the reference case, while the second line the optimal safety factor. It is 1.30; i.e. slightly lower than the reference value. The last column shows the total discounted relative benefits. There is marginal difference between the optimum and the reference case. A further study reveals that the optimum is very flat, i.e. costs do not change much with safety. For that reason one may not want to change the safety, when the total discounted costs do not change much. Further the initial costs (second last column) do not change much either. A higher degree of sensitivity of the benefits to structural reliability is expected if more design parameters are included. Experience from other work [9] shows that for European conditions total benefits are more sensitive to changes in O&M expenses than to changes in reliability. These conclusions are all limited to European conditions. It is of interest to see how all this turns out for Typhoon conditions.

The 5<sup>th</sup> and 6<sup>th</sup> row of Table 4 consider the case of  $U_{\text{ref}}$  equal 60 and 70 m/s, respectively. Compared to the reference cases in rows 3 and 4 a significant drop in safety factors, to a level below IEC 61400-1, and safety is seen. However total benefits do not change as drastically. Table 5 illustrates how relatively small the change in total benefits is with the safety factor. For comparison the consequences of a change in O&M expense of  $\pm 10\%$ , which in the present case equals a change in benefits (profits) of  $\pm 3\%$ , are presented in rows 7 and 8. It turns out that the sensitivity is similar to the change due to cost-optimisation. If the uncertainty on O&M expenses is about 10% this questions the benefits of changing safety to gain on bene-

	Load safety factor: $\gamma_f$							
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
$U_{\text{ref}} = 60$ m/s	-	1.3293	1.3334	1.3302	1.3215	1.3088	1.2933	1.2757
$U_{\text{ref}} = 70$ m/s	1.2081	1.2163	1.2141	1.2040	1.1881	1.1679	1.1446	1.1191

Table 5 The variation of total benefits  $G(z)$  with safety for the typhoon case with different  $U_{\text{ref}}$ .

fits. One should note that the change in safety will be of the order of 4-5 time higher probability of failure – which is some. These results are expected to be less pronounced if  $CoV=25\%$  had been considered.

Recall that though O&M costs are important for the lifetime costs, still this does not affect the optimum in the present, as it appear as a constant term included in the benefits in terms of a reduction of the income pr. kWh. In a more involved cost-benefit model the benefit term could become dependent on design parameters by allowing the rotor diameter to vary. E.g. smaller diameter will then both cause less benefit and lesser loads, which would potentially change the optimum. The reason for fixing the rotor diameter in the present study was exactly to avoid the dependency of the benefit on design parameters so that the study would become less sensitive to the actual site (or region of the Philippines) where the turbine may be put up.

## 8 Conclusions

This initial study has focused only on the influence of extreme loads in stand still (or idling mode) during typhoon conditions, however it must still be kept in mind, as discussed in Section 7, that fatigue and operational loads may be design driving too. The consequences on safety factors and costs of changing the design basis to accommodate typhoon conditions while aiming at the same structural safety as for non-typhoon conditions have been discussed. As expected, increases are seen. Also the possibility of aiming at cost optimal design with possibly lower safety than for non-typhoon conditions have been considered. Whether or not to aim at identical safety is a question of design philosophy. It is noted that a decision on philosophy must be closely related to risk considerations, i.e. consequences of failure vs. probability of failure.

If a design philosophy is chosen that aims at ensuring the same structural reliability in typhoon areas as is implied by the IEC 61400-1 for north European environmental conditions the load safety factor shall increase from 1.35 to about 1.7. It must be appreciated that there is some uncertainty about the proper assumptions for the distribution of the extreme wind speeds in typhoons (see the end of the conclusions) but a safety factor of 1.7 is considered a best estimate with the input available in the present project. Table 3 shows how the safety factor changes with assumptions about the extreme wind distribution for typhoons in the Philippines. Together with the increase in 50-yr wind speed from 50 m/s to 60 m/s or 70 m/s an increase in load factor from 1.35 to about 1.7 yields an increase of extreme loads to 180-250%, and with the model in Eq. (10), a relative cost increase in the range from 20% to 30%.

Though O&M costs are also important the lifetime costs, an increase of 20% to 30% can be a challenge. Of course O&M costs have to be added in a more detailed investigation. Though the cost increase is significant the authors expects that aiming at the same reliability as intended by IEC 61400-1 will be the preferred approach in practical design. Even though the economical risk associated with the alternative, cost-optimal design with lower safety, is lower and is controlled in the development of design guidelines by rigours risk based reliability analyses it is expected that the mental step will simply be too large. It is recommended that the practical implementation of special safety for typhoon areas be in terms of a special wind turbine class to be used in conjunction with the IEC 61400-1 and defining, at least, 50-yr wind speed and safety factors. The authors are aware that steps are taken in Japan to address problems similar to those discussed here – also in the framework of IEC 61400-1. The Japanese code committee seems to aim at increasing 50-yr wind speed and probably the load factor as well and define a special Japanese wind turbine class.

If, on the other hand it is accepted that wind turbines should survive typhoons with lower probability load safety factor below the 1.35 recommended in IEC 61400-1 may be feasible. Initial steps for such an investigation have been taken here. The document provides a very simple cost model for a risk evaluation assuming that the consequence of failure will be purely monetary. That is, it is assumed that there will be no human fatalities and no pollution related to a turbine collapse. The assumption of no human fatalities may be justified by the assumption that it is unlikely that people should deliberately come close to wind turbines in case of typhoons. If a CoV=30% is assumed for the Typhoon environment the results show that safety factors 1.2-1.3 are obtained, i.e. below the IEC 61400-1 value. However, the sensitivity in total benefits appears to be low compared to the changes in safety. This may partly be due to the fact that only extreme loads are considered. Including fatigue could change this. All in all with the present results it is debatable what the benefits would be by reducing safety. As a remark, it is noted these results are expected to be less pronounced if a CoV of 25% had been considered. Because of research resource limitations the model has been based on the European experience. As such the model cannot be expected to be fully valid for typhoon conditions, why cost-optimal structural reliability for turbines in typhoon prone areas should be a subject of further research.

It is emphasised that verification against ground measurements of the extreme wind statistics applied here is crucial for the validation of the results presented. Thus, the inherent uncertainty in the interpretation of satellite images applied to determine the typhoon characteristics used here can be considerable compared to the load safety factor, see [5] for details on the uncertainty of contemporary interpretation methods. In [5] it has been made probable, that the data used to obtain the stochastic model used in the present report for the extreme mean winds in the Philippines are in the right range.

Summing up the conclusions are:

- Turbines designed according to IEC 61400-1 cannot be applied directly if design conditions in terms of 50-yr mean wind speed and load factor change, however,
- if collapses are accepted it might be that it would be feasible to erect turbines initially designed to meet only the demands of the lowest IEC 61400-1 wind turbine class, at least with regard to extreme wind speed.

## 9 Acknowledgements

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## Appendix: the relation between the Gumbel and the “squared Gumbel”

The relation between the mean of the “squared Gumbel” and the Gumbel distribution are derived in [8] and repeated here for easy reference. If the Gumbel distribution is given by

$$F(x) = \exp[-\exp\{-\frac{x-\alpha}{\beta}\}] \quad (17)$$

the mean and std. dev. are

$$\mu = \alpha + \beta\gamma \quad \sigma = \frac{\beta\pi}{\sqrt{6}} \quad (\gamma=\text{Euler's constant}) \quad (18)$$

and the mean and std. dev. of the squared Gumbel variable are

$$\begin{aligned} \mu_{\text{squared}} &\approx \beta^2(\alpha/\beta + \gamma)^2 + (\beta\pi)^2/6 \\ \sigma_{\text{squared}} &\approx \sqrt{\frac{60(\alpha/\beta + \gamma)^2\pi^2 + 11\pi^4 + 720(\alpha/\beta + \gamma)\zeta(3)}{90/\beta^4}} \quad \zeta(3) \approx 1.202057 \end{aligned} \quad (19)$$

Re-arranging Eq. (19) with respect to  $\alpha$  and  $\beta$  one gets

$$\begin{aligned} \kappa \equiv \alpha/\beta + \gamma &\approx \sqrt{\mu_{\text{squared}}/\beta^2 - \pi^2/6} \\ \frac{90\sigma_{\text{squared}}^2}{\beta^4} - 60\pi^2\kappa^2 - 720\zeta(3)\kappa - 11\pi^4 &\approx 0 \quad \zeta(3) \approx 1.202057 \end{aligned} \quad (20)$$

Thus one may solve the latter equation first with respect to  $\beta$  by numerical means and then determine  $\alpha$  afterwards.

Alternatively Eq. (19) may be written

$$\begin{aligned} \mu_{\text{squared}} &\approx \mu^2 + \sigma^2 \\ \sigma_{\text{squared}} &\approx \sqrt{\frac{360\mu^2\sigma^2 + 396\sigma^4 + [\{4320\sqrt{6}\zeta(3)\}/\pi^3]\mu\sigma^3}{90}} \quad \zeta(3) \approx 1.202057 \end{aligned} \quad (21)$$

For  $\sigma$  small compared to  $\mu$  one sees that

$$\frac{\sigma_{\text{squared}}}{\mu_{\text{squared}}} \approx \frac{\mu^2\sqrt{4(\sigma/\mu)^2 + 4.56(\sigma/\mu)^3 + 4.1(\sigma/\mu)^4}}{\mu^2 + \sigma^2} \approx \frac{2(\sigma/\mu)}{1 + (\sigma/\mu)^2} \approx 2\frac{\sigma}{\mu} \quad (22)$$